Final Report

Theoretical and Experimental Studies of Magneto-Rayleigh-Taylor Instabilities

Department of Energy

Award Reference: DE-SC0002590

UM ref. 09-PAF03222/F023838

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July 7, 2013

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1.0 EXECUTIVE SUMMARY

Magneto-Rayleigh-Taylor instability (MRT) is important to magnetized target fusion, wire-array z-pinchs, and equation-of-state studies using flyer plates or isentropic compression. It is also important to the study of the crab nebula. With this DoE grant, and the supplementary NSF grant for student support under the same title, the investigators performed MRT experiments on thin foils, driven by the mega-ampere linear transformer driver (LTD) facility completed in their laboratory. This is the first 1-MA LTD in the USA. Initial experiments on the seeding of MRT were performed. Also completed was an analytic study of MRT for a finite plasma slab with arbitrary magnetic fields tangential to the interfaces. The effects of magnetic shear and feedthrough were analyzed. These activities are relevant to the magnetized liner inertial fusion (MagLIF) concept recently proposed at the Sandia National Laboratories [S. A. Slutz *et al.*, Phys. Plasmas **17**, 056303 (2010)].

2.0 Report on Experiments

Dynamic plasma load experiments were performed on the University of Michigan's 1-MA Linear Transformer Driver facility, Fig. 1. These experiments characterized MRT growth and plasma dynamics on planar-foil plasmas [1,2]. The MAIZE LTD is capable of delivering a 1-MA, < 100 ns risetime drive pulse into a 0.1Ω matched load with a ± 100 kV charge [2,3]. For these dynamic load experiments, the LTD was charged to ± 70 kV to deliver up to 0.7 MA with 170 ns risetime into the foil load.

Fig. 1. UM 1-MA Linear Transformer Driver Magneto-Rayleigh Taylor Experiment.

Fig. 2. Schematic of foil (cathode) and return current plates (anodes)

Low inductance plasma loads utilized a planar, double-current return plate geometry (Fig. 2) with a 400 nm-thick Al (cathode) foil positioned between the anode plates. The foil's initial position between the anode plates determined the net magnetic pressure used to accelerate the foil plasma. This acceleration was used to drive MRT instability [1,2]. The primary diagnostic for characterization of MRT consisted of a two-frame shadowgraphy system with a 100 ps frequency-doubled YAG laser. Calibrated B-dot loops measured the current flow to the load.

The foil images from the 532 nm wavelength laser backlighting diagnostic with sub-nanosecond time resolution successfully captured MRT instability growth developing on both sides of the planar foil load. These measurements were performed for two cases with differing initial foil locations; a large initial offset (Fig. 3), and a small initial offset (not shown). In both cases, the development of MRT was found to be quite similar. An example is shown in Fig. 4. We have recently used the HYDRA code [4] to simulate the 400 nm-thick aluminum foil with current profile similar to the experiment. Figure 5 shows the HYDRA code results at $t = 40$ ns.

Fig. 3. Shadowgraphs of plasma dynamics with laser probing perpendicular to foil current (i.e., in the z -direction in Fig. 2); large initial offset: a) pre-shot foil, b) 38 ns, 0.215 MA, c) 199 ns, 0.6 MA.

The following interpretation emerged from the data, analytic theory, and HYDRA simulation [1]. Initially, when the current was low, the foil was ablated and the plasma rapidly expanded. At this early stage, the electrothermal instability (ET) dominated [5-7]. After this initial stage, the current built up. The foil plasma thickness rapidly

expanded from the initial value of 400 nm to at least 1 mm by 50 ns after start of current. The magnetic pressure increased, providing retardation of the plasma expansion on *both* sides of the plasma slab. It was this retardation on both sides (i.e., acceleration from the light fluid, the magnetic field, to the heavy fluid, the plasma) that led to MRT on both sides, for both the large offset and small offset case (Fig. 3c). In addition, the MRT development of the left surface and the right surface of the ablated plasma slab was completely decoupled, as we determined that the feedthrough factor of MRT between the left surface and the right surface was exceedingly small [1]. Instability growth rate measurements were made on each interface, with an example shown in Fig. 4. Our ideal MHD theory is consistent with the *trend* displayed in the experimental data: the acceleration should be the highest for large offset left side, the lowest for large offset right side, and somewhere in between for small offset either side. However, the substantial variations in the acceleration that are measured directly should have given much larger variations in the experimentally measured growth rates. Simulations using 2D or 3D HYDRA will be required for quantitative comparison.

Fig. 4. Example instability growth rate for large offset, large-acceleration case. Expected, fastest e-folding time (98 ns) measured for this case (left interface of Fig. 3).

Fig. 5: Snapshot of 1D HYDRA simulation of aluminum foil dynamics (normalized scale). Foil is being accelerated to the right by strong magnetic pressure.

We have recently performed experiments on the seeding of MRT on the 400 nm-thick foil [12,13]. We used an existing 150 fs laser micromachining facility to drill arrays of small (40 micron) holes into foils, as well as an array of such holes drilled with a macroscopic period of 2 mm (Fig. 6). The shadowgraphs of both the unseeded foil and seeded foil are shown in Fig. 7. Box-outs (spatially integrated in one direction to reduce noise) from both sides of the seeded foil are shown in Fig. 7c.

a)

b)

Fig. 6. a) Micrograph of an array of 40-micron-diameter holes, and b) 2 mm macroscopic period of micromachined arrays. Drilled into Al-mylar foils by 150 fs laser micromachining system at UM.

Fig. 7. Shadowgraphs of aluminum foil without seeding (a) and with seeding (b). The effect of MRT seeding is apparent, exemplified in the box-outs (c).

3.0 Report on Theory and Simulation

MRT of a finite slab is studied analytically using ideal MHD for the general model consisting of three regions, I, II, and III (Fig. 8). Within each region i , $i = I, II$ and III, we assume $\rho_0 = \text{constant}$, $\mathbf{B}_0 = (0, B_{0y}, B_{0z})$, so that the magnetic field in different regions may assume arbitrary magnitude and direction tangential to the interfaces. This general model allows a critical examination of MRT anisotropy, feedthrough [8], and magnetic shear [9] when the MRT is driven by an arbitrary mix of magnetic and kinetic pressure. It is a substantial generalization of the classical papers by Taylor, Kruskal and Schwartzschild, Chandrasekhar, and Harris. For perturbations of the form $\xi_1(x)e^{i\omega t - ik_y y - ik_z z}$, we derived the eigenvalue ω as a function of $\mathbf{B}_{01}, \mathbf{B}_{02}, \mathbf{B}_{03}, \rho_{01}, \rho_{02}, \rho_{03}, g, \Delta, k_y$, and k_z , when these parameters are assumed to be constant. Figure 9 shows the normalized MRT growth rate, $\bar{\gamma} = -\text{Im}(\omega_1)/\sqrt{kg}$, and the feedthrough factor $F(\omega_1)$ (= the ratio of the interface displacements ξ_α/ξ_β , Fig. 8) for the most unstable eigenmode ($\omega = \omega_1$) [8]. In general, we find that MRT retains robust growth if it exists. However, feedthrough may be substantially reduced if there are magnetic fields on both sides of the slab, and if the MRT mode invokes bending of the magnetic field lines [8]. In Fig. 9, b_u and b_ℓ denotes, respectively, the effect of magnetic tension at the upper (α) and lower (β) interface in Fig. 8.

Fig. 8. The slab model of MRT

**Fig. 9. (a) MRT growth rate, and
(b) the feedthrough factor [8]**

We have analyzed the effect of magnetic shear on the MagLIF concept [9]. As the axial current increases during its risetime, the azimuthal magnetic field it creates may diffuse into the liner, possibly creating a strong radial dependence of the azimuthal magnetic field within the liner. Together with the pre-existing axial magnetic field B_{0z} , the magnetic field within the liner may exhibit a strong magnetic shear, offering the interesting possibility of shear stabilization of MRT. We used a slab geometry to model an equivalent azimuthal field $B_{0y}(x)$ that varies in a prescribed manner within the liner; from zero magnetic shear to infinite magnetic shear, as shown Fig. 10a. Figures 10b-d plot the normalized MRT growth rate, which show that magnetic shear, together with an axial magnetic field B_{0z} on the order of the azimuthal magnetic field B_{00} ($= B_{01y}$ in Fig.

10a), could reduce MRT growth significantly. The magnetic shear has virtually no influence on the feedthrough factor, however [9].

Fig. 10. (a) Model of magnetic shear, and its effect on MRT growth rates with: (b) $b_\ell = 0$ [9], (c) $b_\ell = 0.5$, and (d) $b_\ell = 0.7$. Comparing with the $b_\ell = 0, 0.5$ and 0.7 curves in Fig. 9a, which do not include magnetic shear nor an axial magnetic field, the stabilizing influence of the latter is noted. In Fig. d, only the zero magnetic shear case remains (mildly) unstable.

In addition to the analytic study, we acquired the state-of-the-art capability of the simulation code, HYDRA [10]. Figure 5 shows our 1D simulation of the ablation of the 400 nm aluminum foil. HYDRA is a fully three-dimensional arbitrary-Lagrangian-Eulerian (ALE) radiation-hydrodynamics code developed at Lawrence Livermore National Laboratory. It can utilize state of the art equations of state, models of thermal conductivity, radiation physics, etc. It is currently used at Livermore to model capsule implosions driven by the National Ignition Facility. A 3-D MHD package has recently been developed for HYDRA that will allow for simulations relevant to current experiments on pulsed power machines such as the UM LTD and the Z-machine at Sandia National Laboratories. The MHD package solves Maxwell's equations, along with resistive Ohm's Law, and includes models for electrical conductivity. During the summer of 2012, our graduate student Matt Weis worked at Sandia as a summer intern, with Mark Hess, Charlie Nakhleh, and Adam Sefkow on the verification of the HYDRA MHD package [10]. Various problems, viz, magnetized Noh problem, liner implosion, and flyer plate, were tested. Shown in Fig. 11 is the comparison of the 1D liner implosion model obtained by Matt Weis, whose PhD thesis is in this area.

Recent Ph.D. graduates from the PI's group included Jacob Zier [2] and Matt Gomez [3], who are now regular staff members of the Naval Research Laboratory and Sandia National Laboratories, respectively.

Fig. 11. 1D HYDRA simulations on a liner in the MagLIF regime, with and without resistivity, and their comparison with the 0D analytic model.

Faculty Involved in Research

Y. Y. Lau, Professor and Project Director

Ronald M. Gilgenbach, Professor and Co-Principal Investigator

David A. Chalenski, Assistant Research Scientist

Nicholas M. Jordan, Assistant Research Scientist

Students Involved in Research

Graduate students:

Matt Weis (DoE support), Adam Steiner (DoE support, then NPSC Fellowship), Tyler Fowler (DoE support, MS graduate), Sonal Patel, (NPSC Fellowship, Woman), Anthony Raymond (UM Rackham Fellowship, Latino), David Yager-Eloraga (UM Rackham Fellowship, NSF Fellowship, Latino), Peng Zhang, Ian Rittersdorf, Jacob Zier (Graduated PhD, supported by NPSC Fellowship, now at NRL), Matt Gomez (graduated PhD, supported by NNSA Fellowship, now at Sandia)

Undergraduate students:

Abraham Thurtell (graduated), Justin Ball (graduated, NSF Supplement to this DoE Grant), Lee Gunderson (graduated, NSF Supplement to this DoE Grant), Robert Steinbock (NSF Supplement to this DoE Grant), Matthew Scarpelli (NSF Supplement to this DoE Grant), Mackenzie Roman (NSF Supplement to this DoE Grant, woman), Ryan Leon (NSF Supplement to this DoE Grant, African American).

Publications by UM that were funded by this Research Project

Archival refereed journals: [1], [8], [9]

Graduated PhD theses: [2], [3]

Invited Conference Papers: [11], [12], [13]

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